REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
21-JUL-2003	Conference Proceedings, (not refereed)	

4. TITLE AND SUBTITLE
Efficient Protocols For Integrated Communication And Formation Control In UUV Task Forces

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62435N

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
74-6636-03

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Marine Geoscience Division
Stennis Space Center, MS 39529-5004

8. REPORTING ORGANIZATION REPORT NUMBER
NRL/PP/7440--03-1022

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release,distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS
communication protocol, UUV range

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)*
unclassified	unclassified	unclassified	Unlimited	6	Brian Bourgeois / 228-688-5321

Standard Form 298 (Rev. 8/98)

Efficient Protocols for Integrated Communication and Formation Control in UUV Task Forces

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Abstract

We propose a new message-efficient communication protocol for maintaining ranging and positional formation in a dynamically moving UUV task force. The protocol offers several attractive features including implementation simplicity, low message overhead and robustness. The proposed protocol is not stand-alone, the formational aspects of the protocol are integrated with other aspects of inter-vessel communication, including data transfer and control. Medium access control, data communication and ranging are implemented via an efficient token-vector passing technique. The main feature of our protocol is the efficient encoding of pairwise UUV range information that can be computed simultaneously by all vessels. This enables each UUV to continuously (with each message) update its world-view of the entire formation. Using only reasonable assumptions about underwater accoustic communication, we show that a simple N-element range-vector is suficient for each UUV to obtain and maintain complete state information about the current network topology (in terms of all other UUV positions and ranges between all UUV pairs) within $1 + \frac{1}{N}$ token-vector trip times.

1 Introduction

The Naval Research Laboratory (NRL) and Louisiana State University (LSU) are developing navigation and communication methods that will enable formation maneuvering of multiple unmanned underwater vessels (UUVs). The immediate focus of this effort is on a long transit from offshore to near shore and, as emphasized in [1], with the minimal use of external positioning aids such as GPS and acoustic transponders. Difficulties encountered in this objective are the cost and size of high-grade inertial systems and the likelihood that water depths may exceed the range of Doppler Velocity Logs (DVLs) on smaller vessels. For many vessels in the group it is assumed that only low-grade navigation packages are practical, typically a magnetic compass for heading and screw rate for speed, so that their estimate of both position and velocity are poor. Consequently, the approach taken here is that a few 'host' vessels within the formation will have high-grade inertial navigation systems and the remaining 'follower' vessels will be required to navigate relative to these hosts.

The focus of this paper is on the development of an efficient protocol for the exchange of positioning and navigation information between vessels in a formation. Communication underwater is practically limited to acoustic methods, and Kilfoyle and Baggeroer [2] provide an extensive review of the state of the art in underwater acoustic telemetry. The dominant features of the underwater acoustic telemetry channel of concern here are slow propagation, limited range, vessel power consumption and narrow bandwidths. Achieved acoustic modem throughputs are on the order of 1000 bps for

incoherent systems and 10,000 bps for coherent systems. While ongoing research is increasing the capabilities of acoustic modems the available throughput must be shared for all formation functions including data transmission and command and control, so it is prudent and the objective of this work to develop a scheme that will minimize telemetry requirements for the formation-maneuvering task.

An enabling factor for formation maneuvering of UUVs is the recent merging of underwater communications and positioning technologies [3]. Historically, communication and positioning systems required separate hardware, increasing the cost, size and power consumption of the UUV, resulting in contention between systems for the same frequency spectrum, and allowing only single users. New acoustic modems developed by WHOI not only support multi-users and interaction with long base line (LBL) positioning systems, but are also able to provide measurement of inter-vessel travel time with an accuracy on the order of 0.2ms [4] and the mean Doppler shift (range rate) between vessels.

2 Related Work

Recent works on underwater networking include Sozer et al. [5] that focuses on networks covering very large areas with infrequency bursty communications, while our effort is concerned with smaller areas and continuous exchange of information between vessels at a constant rate. While the work in this paper initially considers a fully-connected peer-to-peer network, [5] indicates the potential overall power advantage of using message relaying and this will be examined in future work. Freitag et al. [3] present an example of integrated acoustic communications and positioning with both active and passive approaches, but the use of fixed nodes limit the applicability to the long transit scenario. Stojanovic et al. [4] present a time division multiple access (TDMA) protocol for a group of UUVs working cooperatively, where the information passed between vessels is used to improve upon individual position estimates obtained with GPS-aided inertial systems or long-baseline. In [4] clock synchronization between vessels is assumed thus enabling one way ranging between vessels, while in this paper we consider unsynchronized clocks requiring two-way ranging and the consequential higher network usage.

3 Task Force Formation Maintenance: Design Issues

The specific problem that we consider is as follows: Is there a simple and message-efficient communication protocol by which all the vessels in a (small) UUV task force formation can,

1. *Obtain* relative positional and navigational information from all other vessels in the formation, in effect, a continously updated world-view of the current task force configuration.

2. *Maintain* their positions with respect to other vesssels in the task force by adjusting their navigational and positional actions based on the above obtained world-view of the overall task force topology and motion.

Clearly, the second objective depends on the complexity of the control algorithm at each vessel, which in turn is a function of the 'quality' and 'amount' of state information that each vessel possesses about the rest of the network[1]. This state information can be local involving the vessel's own navigational and positional information along with limited neighborhood vessel parameters, or global including overall network topology with respect to range and bearing between vessels, their velocities, relative drift etc. For example, potential based formation control algorithms use proximity information as a factor.

Our premise is that *global* state information such as bearing, range and velocities are crit-

[1]We use the terms task force and network interchangeably in this paper.

ical to controlling and maintaining tight network formation, particularly if such information can be exchanged in an efficient manner. Therefore in this paper we focus on the development of an efficient communication protocol that will enable the transmission of global state information using minimum number of messages. We are primarily interested in achieving 'multivessel' ranging i.e., all vessels in the formation are aware of the range and bearing of every other vessel with respect to themselves and each other. Most existing ranging protocols are predicated on obtaining location and ranging information with respect to either a single host vessel (as a baseline) or with respect to neighboring vessels only. While this approach may be less communication intensive, it is possible for small local errors to accumulate thereby making the overall formation unstable. It is therefore of interest to determine the cost-benefit tradeoffs of enabling dissemination of global state information to all the vessels in the formation. Obviously, this message dissemination protocol has to be efficient in terms of message complexity tobe useful. Indeed, it is unlikely that such an approach will work for a large UUV network. However it may prove to be efficient for small, tight networks or hierarchical formations in which vessels are grouped into tight clusters. Thus to demonstrate proof-of concept and for ease of verification through simulation, we assume a small UUV formation along with other assumptions listed below.

1. **Omnidirectional hydrophones**: The directional nature of accoustic reception imposes significant restrictions on underwater communication. The use of traditional limited degree hydrophones do not leave much room for orientation error. Even a slightly disoriented UUV within range will be unable to receive messages, leading to high retransmission overheads and imposing an additional UUV formational constraint of correct orientation. Using omnidirectional hydrophones will alleviate this problem leading to higher message efficiency and simpler formation control and messaging protocols. The feasibility of deploying omnidirectional hydrophones has been demonstrated.

2. **Regular network topology**: We assume that the underwater vessels are formed initially into a regular configuration such as a star, with the control UUV at the center of the star.

3. **Two communication channels**: We assume the existence of a low-frequency, long-range accoustic channel that can be used by the control UUV for broadcasting to all the UUVs in the formation for command/control emergencies, nodes accessing or leaving the network, and to restart/repair the task force formation protocol in case of unrecoverable messaging protocol errors. A second high-frequency channel is used for inter-UUV communication. Note that if the formation is tightly packed within a small range, messages on the high frequency channel can be received by all UUVs, therby functioning as a de-facto broadcast channel. While this is not a functional requirement for the proposed protocol, we will exploit this feature to increase protocol efficiency.

4. **In-formation messaging protocol**: Our protocol will maintain the task force formation once formed, by periodically passing required information to formation control algorithms on board each vessel. The problem of arriving at the initial formation is beyond the scope of this paper.

Based on the above assumptions, any messaging protocol should have the following properties:

- **Efficiency**: Due to high messaging overheads, the protocol has to be efficient in terms of message complexity, number of messages, and state update frequency at each vessel.

- **Robustness**: The protocol has to be robust to account for underwater operational limitations. Multipath interference and fading effects on accoustic transmission along with difficulties in accurate navigation due to ocean currents can lead to high message error rates. Difficulties in clock synchronization and lack of multiple communication channels significanty constrain the number of feasible messaging protocol solutions.

- **Integration**: The messaging protocol for multi-vessel ranging should not be standalone, but integrated with other aspects of inter-vessel communication. Vessels should be able to determine relative positioning, ranging and other information without being *tethered* to a separate network or protocol for positioning and ranging. For example, one option is for the entire formation to periodically get a GPS fix using special hardware, However, taking time off to establish GPS positions consumes significant overhead and also requires some form of synchronization among vehicles. Alternatively, the entire formation can ping off a fixed network of buoys, as described in the literature. This scheme is not fault-tolerant as it is affected by external failure points (the buoy network).

4 An Efficient Protocol for Formation Maintenance

Consider a task force of N UUVs arranged in a pre-fixed formation with a control vessel in the center and moving as a group towards a given objective. This formation is expected to be maintained most of the time. However the control UUV may periodically provide explicit instructions for formation rearrangement. This will require each vessel to be aware of its relative position in the formation, including its range to other vessels. Thus the communication protocol between vessels must enable data communication by regulating medium access and include features for multi-vessel ranging and formation maintenance. The main features of the protocol are described below:

The medium access control mechanism in our protocol is *token based with a range-vector* for enabling each UUV to compute its range relative to every other vessel in the formation. A vessel requires a token in order to transmit. Tokens are passed between adjacent neghbors in orderly fashion. We assume that the formation is small and underwater available bandwidth is scarce. Thus only a single transmission frequency is available and all transmissions are broadcast transmissions, i.e., all vessels are within efective reception range (though this is not necessary for the protocol to work). Each vessel has its own clock operating asynchronously (since synchronization between vessels is an expensive process).

Consider a message sent by UUV i, $1 \leq i \leq N$, during message round t, where a message round is completed when the token makes a round trip through the N UUVs with each node obtaining the token once. Each message is divided into header and data segments with the header consisting of three main fixed-length fields as follows: First, a fixed-length token identifier validates the message. This is followed by an N-element range-vector. The jth element of the range-vector $\vec{R}_i^t$, $1 \leq j \leq N$, consists of a tuple $< A_{ij}^t, B_{ij}^t >$ which can be used to calculate the range between vessels i and j *by all vessels in the formation*, in the manner explained below. The range-vector is followed by a message length field containing the total size of the message. Finally, the variable length data segment contains data items (if any) segments for each of the remaining vessels. Data items include acknowledgements for previously transmitted data packets along with other encapsulated higher protocol layers. The message is terminated by the token which is then released to the vessel adjacent to UUV i.

The main feature of our protocol is the efficient encoding of pairwise UUV range information that can be computed simultaneously by all N vessels. This enables each UUV to continuously (with each message) update its world-

view of the entire formation. Instead of pinging separately off a baseline for individual ranging information, the range-vector $\vec{R}_i^t$ enables simultaneous ranging. The primary challenge to be overcome is the asynchronous clock at each UUV and this is done as follows:

Let $\mathcal{C}_i$ represent the normalized rate of UUV i's asynchronous clock, not shared by other UUVs. Consider two successive rounds of messages t and $t+1$ (i.e., two token round trips) between all UUVs. Without loss of generality assume that i precedes j in the token passing order. During round $t+1$, the A_{ij}^{t+1}th field in the range-vector sent by UUV i contains the time interval (as measured at UUV i in terms of its clock) between the last message sent by i and the last message received by i from j, both during round t. (Note that for UUV j during round $t+1$, this field should contain the interval between the last message sent by j in round t and the message from i received in round $t+1$). Thus A_{ij}^{t+1} *contains* (but is not the same as) the ranging time from i to j during round t. Also during round $t+1$, UUV i sets the B_{ij}^{t+1}th field in its range-vector to the time elapsed since the receipt of j's message in round t and the start of i's message in round $t+1$. (For UUV j, this field will contain the time elapsed since i's message and j's reply in round $t+1$). Note that since each message also contains a message length field, these time intervals can be adjusted so as to eliminate the effect of packet transmission times.

Let $\mathcal{R}_{ij}^t$ be the average range-time betwen UUVs i and j during a message round, where range-time is the time for an accoustic signal to travel from i to j and bounce back. This time can then be used to calculate the physical distance between the two vessels. In our protocol, the actual range-time is not directly measured but it is contained in the A field described above. However this field also contains the packet processing times at i and j along with other delays, which must be discounted[2].

[2]For simplicity, we do not consider packet transmission times in our derivation. Since packet lengths are known exactly from each header, they can be easily accounted for.

The B field contains these delays and hence the actual range-time can be calculated as follows:

$$\mathcal{R}_{ij}^t = A_{ij}^{t+1}\mathcal{C}_i - B_{ji}^t\mathcal{C}_j \qquad (1)$$

Similarly in round $t+1$, the range can be expressed as

$$\mathcal{R}_{ji}^{t+1} = A_{ji}^{t+1}\mathcal{C}_j - B_{ij}^{t+1}\mathcal{C}_j \qquad (2)$$

After receiving i's message in round $t+1$, UUV j has all four A and B values available. Based on j's world-view of relative velocities and drifts during each period (as determined by its control module), the relation between ranges in successive periods can be estimated. For example, using a simple exponentially weighted memory model, we have

$$\mathcal{R}_{ji}^{t+1} = (1+\epsilon(t))\mathcal{R}_{ij}^t \qquad (3)$$

where $\epsilon(t)$ represents the expected drift between i and j during period t. For any given model relating range drifts, Equation 1 and Equation 2 can be simultaneously solved at vessel j to obtain the current range-time (and hence range) between UUV i and UUV j. Thus as soon as j transmits its message during this round, every other UUV can solve and obtain the current range between UUVs i and j, $1 \leq i < j \leq N$. After every N messages (i.e one token round trip time), the range between every pair of UUVs in the formation is known at every UUV.

Since the A and B fields in Equations 1 and 2 represent *time intervals* between messages, our protocol is truly asynchronous with respect to message exchanges. It is flexible enough to calculate inter-UUV ranges in spite of variable delays due to messages of different lengths, time elapsed for token management due to token loss during a message round, and delays due emergency interrupts on the control channel. The token round trip time should not be too large since the rate of drift between UUVs during this time is also a factor. However this can be justified by by assuming small formations.

5 Conclusion

We have presented a message efficient token passing protocol that enables every UUV in a formation to continously calculate and update ranges between all pairs of UUVs every token round trip time of N messages. The protocol integrates ranging and formation maintenance with data communication and have very low overhead. In future work, we plan to investigate the efficiency of our protocol for larger formation sizes, particularly in the context of multihop networks. Experimental results will be obtained through a new multiphase underwater network simulator with integrated communications and control modules, currently being developed at the Naval Research Laboratory.

References

[1] T.B. Curtin, J.G. Bellingham, 'Guest Editorial Autonomous Ocean-Sampling Network', IEEE Journal of Oceanic Engineering, vol. 26, no. 4, October 2001.

[2] Kilfoyle, D.B. and Baggeroer, A. B., 'The State of the Art in Underwater Acoustic Telemetry', IEEE Journal of Oceanic Engineering', vol. 25, no. 1, JAN 2000.

[3] Lee Freitag, Mark Johnson, Matthew Grund, Sandipa Singh and James Presig, 'Integrated Acoustic Communication and Navigation for Multiple UUVs', Proceedings of the IEEE Oceans 2001 Conference', Honolulu, HI, pp. 2065-2070, November 2001.

[4] M. Stojanovic, L. Freitag, J. Leonard and P. Newman, 'A Network Protocol for Multiple AUV Localization', Proceedings of the IEEE Oceans 2002 Conference, pp. 604-610.

[5] Sozer, E.M.; Stojanovic, M.; Proakis, J.G.; 'Underwater acoustic networks' IEEE Journal of Oceanic Engineering, Volume: 25 Issue: 1 , Jan 2000 Page(s): 72-83.